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Neurophysiological evidence for evaluative feedback processing depending on goal relevance

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ABSTRACT

Feedback signaling the success or failure of actions is readily exploited to implement goal-directed behavior. Two event-related brain potentials (ERPs) have been identified as reliable markers of evaluative feedback processing: the Feedback-Related Negativity (FRN) and the P3. Recent ERP studies have shown a substantial reduction of these components when the feedback's goal relevance (in terms of goal informativeness) was decreased. However, it remains unclear whether this lowering of evaluative feedback processing at the FRN and P3 levels (i) reflects a common regulation process operating across them or (ii) indirectly and mostly depends on valence processing. To address these questions, 44 participants performed a time estimation task wherein the perceived goal relevance of the feedback following each decision was manipulated via instructions in different blocks. We recorded 64-channel EEG and collected subjective ratings of feedback valence and relevance, separately for goal-relevant and irrelevant conditions. ERP results showed a substantial reduction of the FRN and P3 components for irrelevant than relevant feedback, despite the balanced task relevance between them. Moreover, a Principal Component Analysis (PCA) showed that these two successive ERP effects had dissociable spatiotemporal properties. Crucially, a multivariate multiple regression analysis revealed that goal relevance per se, but not valence, was the unique significant predictor of the amplitude reduction of the FRN and P3 when the feedback was goal irrelevant. Our results suggest that although these ERP components exhibit non-overlapping spatiotemporal properties and performance monitoring effects, they can both be modulated by a common, valence-unspecific process related to goal relevance.

1. Introduction

Continuous evaluation of action outcomes is crucial in goal attainment. When a prediction error occurs (i.e., a deviation between the actual and predicted outcome), specific performance monitoring (PM) processes allow to rapidly detect this mismatch, and subsequently trigger corrective measures, to foster goal-adaptive behavior and self-regulation (Botvinick and Braver, 2015; Ferdinand and Czernochowski, 2018; Hofmann et al., 2012; Inzlicht et al., 2014). Contemporary neurophysiological models of PM assume that a feedback loop enables the rapid detection and updating of prediction errors (Holroyd and Coles, 2002; Ullsperger, 2017; Ullsperger et al., 2014). Importantly, this feedback loop is not free from external influences, but amenable to goals and contexts, which yields dynamic and flexible changes (Ullsperger et al., 2014). This feedback loop exploits either internal/motor information (e.g., response errors) or external/feedback information (e.g., evaluative stimulus) to readily assign values to actions and influence subsequent decision making processes.

At the event-related brain potential (ERP) level, specific components reflecting the operations of this feedback loop have been identified in the past. In particular the Feedback-Related Negativity (FRN)[1] occurs when PM operates based on external evaluative feedback stimuli (Miltner et al.,

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[1] Since its discovery, the FRN has also been referred to as the *feedback-ERN* (fERN), the *feedback negativity* (FN), and the *medial-frontal negativity* (MFN), leading to nomenclature confusion in the literature (see Krigolson, 2018). More recently, reference to the FRN as a "negativity" has been challenged. This contention stemmed from reports showing modulation of the component's positive conditional waveform, as opposed to the negative one (e.g., Foti et al., 2009; Krigolson et al., 2014), especially when focusing on reward processing per se (Gheza et al., 2018; Krigolson, 2018). Consequently, some authors have advocated relabeling the FRN as the *reward positivity* (RewP; Proudfit, 2015) and the *feedback correct-related positivity* (fCRP; Holroyd et al., 2008).

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1997). If a negative and/or unexpected feedback is provided, a negative deflection is elicited, peaking 250–300 ms after stimulus onset at fronto-central electrodes. Moreover, following the FRN, a large positive deflection is elicited, peaking 300–600 ms after feedback presentation at posterior parietal sites along the midline, in agreement with a P3 component (Desmedt et al., 1965; Donchin and Coles, 1998; Polich, 2007; Sutton et al., 1965).

Different dimensions that characterize outcome feedback have been demonstrated to modulate the amplitude of the FRN and P3 components. Various studies have reported increased FRN amplitudes for unfavorable outcomes or negative feedback relative to favorable outcomes or positive feedback (Gehring and Willoughby, 2002; Miltner et al., 1997; Nieuwenhuis et al., 2004), as well as for unexpected compared to expected outcomes (Alexander and Brown, 2011; Ferdinand et al., 2012; Hajcak et al., 2005; Hajcak et al., 2007; Pfabigan, Alexopoulos, Bauer and Sailer, 2011). Furthermore, outcomes of greater magnitude (Goyer et al., 2008; Gu et al., 2011) or higher salience (Talmi et al., 2013; Hauser et al., 2014; Soder and Potts, 2018; Walentowska et al., 2019; Yeung et al., 2005) have also been related to a larger FRN component. As for the P3 component, studies have reported increased amplitudes for positive compared to negative feedback (Bellebaum and Daum, 2008; Pfabigan et al., 2011) and for outcomes of greater magnitude than for those of lesser degree (Bellebaum and Daum, 2008; Yeung and Sanfey, 2004). The P3 component has been suggested to reflect motivational effects (Aston-Jones and Cohen, 2005; Nieuwenhuis et al., 2005; San Martín, 2012), with larger amplitudes likely reflecting the enhanced motivational significance of the feedback in some conditions. Alternatively, this component may reflect a selective (working memory) updating process whereby the action's value is modified, especially when prediction errors occur and are conveyed by the feedback stimulus (Fischer and Ullsperger, 2013; Polich, 2007; Ullsperger, 2017; Ullsperger et al., 2014).

Although the link between the FRN component and evaluative feedback processing is evident and undisputed, there is still a lack of consensus in the existing literature regarding the specific stimulus dimension (or combination of dimensions) that drives the amplitude variations of this component during PM (Hajihosseini and Holroyd, 2013; Krigolson, 2018; Proudfit, 2015; San Martín, 2012; Ullsperger et al., 2014). Some researchers have proposed feedback valence as a key dimension (i.e., negative feedback elicits the FRN), while others have suggested expectancy instead (i.e., unexpected feedback elicits the FRN), or a combination of both (i.e., unexpected negative feedback elicits the FRN; for reviews, see Holroyd and Umemoto, 2016; Sambrook and Goslin, 2015; Walsh and Anderson, 2012). Moreover, in most experiments, the feedback stimulus is usually more complex than merely informing about a binary good vs. bad decision, suggesting that the FRN could very well capture other PM effects besides valence or expectancy alone (Holroyd and Yeung, 2012; Sambrook and Goslin, 2015; Threadgill and Gable, 2018; Ullsperger et al., 2014). In agreement with this view, several studies have recently investigated the influence of goal information on PM (Gentsch et al., 2013; Osinsky et al., 2012; Threadgill and Gable, 2016, 2018), including goal relevance (Severo et al, 2017, 2018; Walentowska et al., 2016; Walentowska et al., 2018). In these latter studies, we showed that the FRN was not only sensitive to valence and expectedness, but also to goal relevance (see Severo et al., 2017, 2018; Walentowska et al., 2016). We proposed that goal relevance can be broken down into three dissociable aspects embedded in a hierarchical structure (Walentowska et al., 2016): (i) task relevance (lowest level), which is the extent to which the feedback stimulus allows for the implementation of a task goal, (ii) goal informativeness (intermediate level), which is the extent to which the feedback stimulus reliably informs about the satisfaction status of pursued goals, and (iii) goal impact (highest level), which is the extent to which the feedback impacts the satisfaction of a goal.

In a proof-of-concept study (Walentowska et al., 2016), we focused on goal relevance in the sense of goal informativeness and explored the amplitude variations of the FRN and P3 components as a function of it. To this aim, participants performed a speeded Go/No Go Task (Aarts and Pourtois, 2010, 2012; Koban et al., 2010; Vocat et al., 2008) in which correct actions were followed by either positive or negative feedback depending on their reaction times (RTs). Only correct and fast go decisions—which had a low probability—were accompanied by the presentation of a positive evaluative feedback. In contrast, correct but slow go decisions were followed by a negative feedback. In some blocks, this feedback reflected participant's actual behavior and was therefore relevant in the sense of informing him/her about the satisfaction status of his/her goal. In other blocks, the positive or negative feedback was independent of participant's actual behavior and was therefore irrelevant in this sense. Importantly, in these two conditions, the probes to the feedback made it always task relevant (lowest level), to ascertain that goal informativeness was the main dimension on which both conditions differed. ERP results showed larger FRN for negative compared to positive feedback, but only when the feedback was relevant. This effect suggests that the early processing of the action value could be suppressed when the feedback was not informative about goal satisfaction. In a second experiment (Walentowska et al., 2016), we increased reward (positive feedback) probability and found that the interaction effect between valence and goal relevance shifted from the FRN to the P3. A larger P3 was found for negative than positive feedback, but again only when this feedback was relevant in the informative sense. We interpreted these neurophysiological findings using a hierarchical model of PM (Walentowska et al., 2016; but see also Holroyd and Yeung, 2012) in which goal relevance operates at a superordinate level, expectedness at an intermediate level, and valence at a subordinate level.

These previous ERP results suggested that lowering the feedback's goal relevance in the sense of goal informativeness (from now on referred to as goal informativeness for simplicity) led to a systematic amplitude decrease of both the FRN and P3 components. Based on these findings only, however, it remains unclear whether this effect (i) arose from a common regulation process and was directly related to relevance as we surmised (Walentowska et al., 2016), or (ii) operated indirectly, mostly via changes in valence processing. Moreover, these previous ERP studies had some methodological limitations. First, the results were obtained using the Go/No Go Task that involves motor inhibition (Aron, 2007). Accordingly, an open question is whether the influence of goal informativeness on the FRN component could also be found when another PM task is used in which motor inhibition is not required. Given that we assume goal informativeness to be a superordinate PM factor, it should not be bound to a specific task. Second, the previously found effect was established using a subset of trials only. Given the nature of the Go/No Go Task, the analysis in our previous study only included the feedback following overt responses on Go trials. We reckoned that only for these trials the outcome was uncertain (and hence the feedback was the most informative; see also Walentowska et al., 2018 for an indirect confirmation). Consequently, we had to remove from our analyses the feedback following No-Go trials, for which the outcome was certain (and no overt action occurred). Third, we used facial expressions as evaluative feedback because of their enhanced ecological validity and to increase its impact, but this may have introduced an unwanted level of complexity (Pfabigan et al., 2019; Pfabigan et al., 2015) that resulted in a somewhat non-canonical FRN morphology.

To overcome these limitations, in this study, we applied the previously used goal informativeness manipulation (Walentowska et al., 2016) to a time estimation task (Miltner et al., 1997,). This task entails reliance on external feedback, which makes it ideal to explore evaluative feedback processing at the ERP level, and probably explains why so many PM studies have used it in the past to explore the FRN component (Boksem et al., 2012; Miltner et al., 1997,; Pfabigan et al., 2019; Pfabigan et al., 2015; Pfabigan et al., 2014). In the current study, participants completed a modified version of this task (Miltner et al., 1997,; Pfabigan and Han, 2019; Pfabigan et al., 2015, 2014), in which they received evaluative feedback that was relevant in some blocks but not in others (in analogy with Walentowska et al., 2016). Participants had to estimate a time interval and monitor the evaluative feedback provided afterwards that informed about the accuracy of this estimation (Holroyd and Krigolson, 2007; Miltner et al., 1997). Prior to each block, written instructions as well as a distinctive visual cue were provided to the participants to indicate whether the feedback was informative or uninformative. Importantly, in both conditions, the evaluative feedback was always task relevant (as secured with catch trials). Importantly, we also collected subjective ratings of feedback informativeness and valence for each condition separately. We subsequently used these ratings to assess, using a multivariate regression analysis, whether these two dimensions (i.e., informativeness and valence) significantly contributed to explain the difference in amplitude changes of the FRN and P3 components between these two conditions.

We hypothesized a significant interaction effect to occur between goal informativeness and valence at the FRN level based on our previous results (Walentowska et al., 2016). More specifically, we predicted a larger amplitude difference at the FRN level between negative and positive feedback when they were embedded in blocks in which they were informative, compared to blocks in which they were uninformative. We also predicted that goal informativeness would influence the subsequent P3 globally, reducing its amplitude when the feedback was uninformative, but irrespective of its valence. Hence, we expected to obtain dissociable effects for the FRN and P3 during evaluative feedback processing and a modulation of these effects by goal informativeness. Furthermore, considering that these two ERP components occur in rapid succession, we performed a principal component analysis (PCA) to ascertain that goal informativeness exerted dissociable effects on these components. Last, by means of multivariate regression analyses, we could assess whether goal informativeness was indeed the factor driving the amplitude changes of the FRN (and possibly P3) across the two main conditions, as we hypothesized (see also Walentowska et al., 2016), or whether alternatively, valence mostly accounted for them.

2. Materials and methods

2.1. Participants

An *a priori* power analysis was performed to estimate the sample size using MorePower v6.0 (Campbell and Thompson, 2012) based on the effect size reported in our previous work (see Experiment 1 of Walentowska et al., 2016). This analysis estimated that for a 2x2 repeated-measures ANOVA and an alpha of 0.5 (2-sided), a sample size of 44 participants has sufficient power (80%) to detect the significant interaction effect between goal informativeness and valence at the FRN level ($\eta_p^2 = 0.159$). Fifty-six healthy, right-handed students were initially recruited in exchange for a fixed monetary compensation. Four participants were excluded because of excessive noise and artifacts during the electrophysiological recording and eight others because they had low accuracy on the catch trials.[2] Thus, the final sample size consisted of 44 participants (6 males; aged = 18–28 years old; $M = 22.32$; $SD = 2.73$). All participants were recruited via an online scheduling system and gave written informed consent to take part in compliance with the Declaration of Helsinki. They had normal or corrected-to-normal vision, with no reported color blindness or current treatment for neurological or psychiatric illnesses. The study was approved by the local ethics committee of Ghent University.

Consistent with our previous work (Walentowska et al., 2016), individual differences in trait anxiety and perceived locus of control were assessed considering that these dispositions can influence PM at the FRN level (Aarts and Pourtois, 2012). Participants completed the Dutch versions of the STAI-trait (Defares et al., 1980; Spielberger et al., 1970) and the Locus of Control (LOC) questionnaire (Rotter, 1966). The mean STAI score was 42.41 ($SD = 9.47$; range: 27–61) and the LOC score 13.59 ($SD = 4.18$; range: 5–21). Exploratory correlation analyses were performed between these dispositions and the FRN's amplitude (as well as P3), but they failed to reveal significant effects and are therefore not reported here.

2.2. Experimental design and task

We conducted a modified version of the time estimation task (Miltner et al., 1997; Pfabigan and Han, 2019; Pfabigan et al., 2015, 2014) with a within-subject design. Participants had to estimate the elapse of 1-s and to report it by pressing a predefined key. After each estimation, performance feedback was provided and embedded into two conditions that differed with regard to goal informativeness. As in our previous studies (Walentowska et al., 2016, 2018), this manipulation was achieved by varying in an all-or-none fashion the contingency between the response and the feedback in different blocks, while keeping the stimuli and task demands unchanged across conditions. The two conditions (informative vs. uninformative) were introduced to the participants through (i) written instructions and (ii) a cueing technique that clearly demarcated the conditions from each other. Specifically, the instructions were provided at the beginning of each block and a specific frame (either a square or a diamond) was presented. The instructions for the informative condition specified the frame with the text: *"This frame indicates that the feedback is REAL (i.e., related to your performance)."* The instructions for the uninformative condition specified the frame with the text: *"This frame indicates that the feedback is NOT REAL (i.e., NOT related to your performance)."* Apart from seeing the frame during the delivery of the instructions, participants saw the condition-specific frame from the response onset until feedback offset. Additionally, catch trials were included to make sure that the feedback in both conditions remained task relevant. In 16% of all trials (i.e., 32), participants were probed about the information conveyed by the previously seen feedback (i.e., whether it was positive or negative). They were told that responding accurately was important and were given no time limit.

The experimental design and a sample trial sequence are presented in Fig. 1. Each trial began with a black fixation dot presented for 1000 ms. Afterwards, a black star serving as the cue for the onset of the time estimation was shown for 250 ms. This event was followed by the presentation of a blank screen (1750 ms) during which participants had to indicate the passing of 1 s by pressing the number 3 key of a response box with the index finger of their right hand. Each key press was followed by the presentation of the condition-specific frame to indicate that a response had been registered. Two thousand milliseconds after the star onset, the feedback was presented inside the condition-specific frame for a duration of 1000 ms. The feedback was a color-coded dot: green for positive feedback and red for negative feedback. In case no key press was recorded within the allotted time, a text stating 'too late/no response' was displayed. Finally, the inter-trial interval was depicted by the black fixation dot, which had a jittered duration of 1400–1600 ms. All visual stimuli were centrally presented on the screen against a gray background. The task was implemented in E-prime V2.0 (Psychology Software Tools Inc., Sharpsburg, PA) and presented on a 19-inch CRT screen.

To make sure that comparable numbers of correct and incorrect responses were given and thus comparable numbers of positive and negative feedback were received, task difficulty was adjusted to the individual performance level, albeit unbeknownst to participants. To this end, the width of the response time window was calibrated as follows (Miltner et al., 1997; Pfabigan et al., 2014): Each participant began with a time window, in which a response was deemed as timely if it fell between 900 and 1100 ms after the onset of the star. Following a trial with

[2] We introduced catch trials (see Experimental design and task section) to make sure that participants attended to the evaluative feedback, especially in the uninformative condition. We set a performance cut-off of 62,5% to increase the likelihood of balancing the two main conditions along this variable, as accuracy on catch trials tended to irremediably decrease for the uninformative condition (see Results section). A control analysis was run (see Supplementary Materials) in which we included these eight participants, but the results (e.g.,. for the FRN) remained unchanged at the group level.

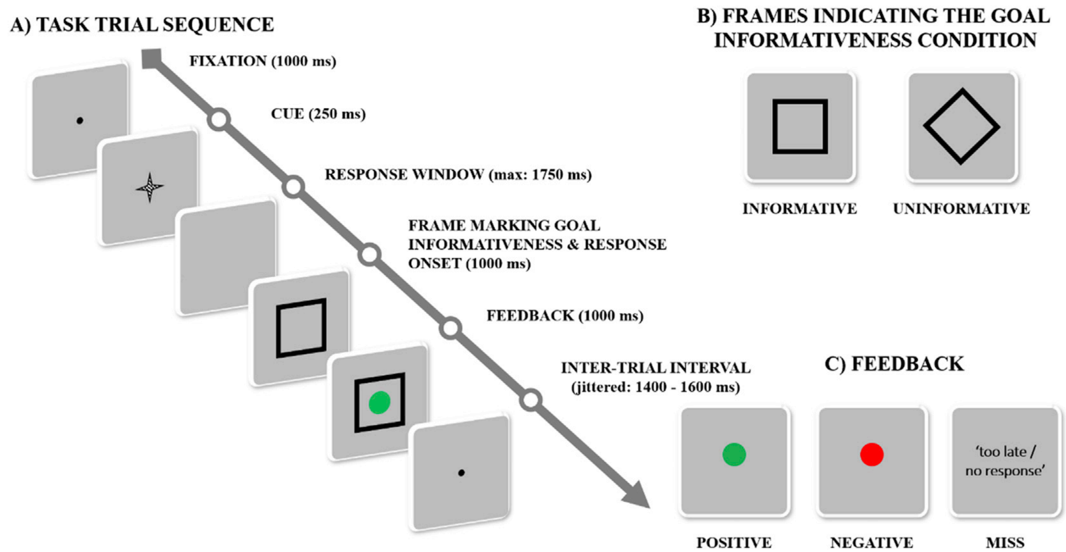

Fig. 1. Procedure. (A) Example of a trial of the time estimation task (see Methods). Every trial started with a fixation dot shown for 1000 ms, followed by a black star displayed for 250 ms. This cue signaled the onset of the time estimation. Participants were instructed to press a predefined key when 1 s had elapsed. At response onset, a black frame appeared before performance feedback (in the form of a color-coded dot) was provided to the participants for 1000 ms. (B) The frame was either a square or a diamond, and indicated whether the upcoming feedback was goal informative or not. The mapping between goal informativeness and the shape of the frame was counterbalanced across participants. (C) A green dot was used for positive feedback, a red dot for negative feedback, and a text stating 'too late/no response' for misses.

positive feedback, the time window was narrowed down by 10 ms at both ends. Following a trial with negative feedback, the time window was widened by 10 ms at both ends. This calibration procedure was used for the informative condition. No calibration was used for the uninformative condition. Instead, a fixed and equal number of negative and positive feedback was delivered randomly, irrespective of accuracy. The experiment was composed of a short practice block (6 trials, always with a relevant feedback) and four experimental blocks (each having 50 trials). Each condition (informative vs. uninformative) included two blocks. We alternated the order of presentation of blocks across participants creating two specific orders: I–U–I–U or U–I–U–I, with I referring to the informative and U to the uninformative condition.

Subjective ratings of the feedback's goal informativeness were registered to verify whether our informativeness manipulation had been successful. This manipulation check was performed (i) after each block and (ii) at the end of the experimental session. These ratings were also used as predictors in the multivariate regression analyses (see here below). Participants evaluated how much the feedback reflected their performance (i.e., estimation accuracy) during the block just encountered. For the post-experiment ratings, participants evaluated how much the feedback embedded in the condition-specific frame reflected their performance. Moreover, they rated how much they liked the positive and negative feedback embedded in the condition-specific frame. For all the questions, a visual analogue scale (VAS) ranging from 0 (not at all) to 100 (a lot) was used.

2.3. Procedure

The experimental session began with participants signing the informed consent. They attended the session one at a time and received general instructions in preparation for the EEG recording. Afterwards, the experimenter attached the EEG sensors and participants performed the computerized experimental procedure in an acoustically and electrically attenuated room under dim lighting condition. The procedure started with the practice block to acquaint participants with the time estimation task, followed by four experimental blocks, and post-experiment ratings. The session ended with the experimenter debriefing the participants.

2.4. Behavioral analysis

The behavioral data was composed of the catch-trial accuracy (i.e., in percentages), the performance indices (i.e., number of correct estimates expressed in percentages and estimate accuracy in milliseconds), the post-feedback behavioral adjustment, and the VAS ratings for feedback informativeness and affective evaluations. For the trial-to-trial behavioral adjustment following feedback in the time estimation task, we compared if the RT on the subsequent trial was either closer to the target of 1000 ms (i.e., correct adjustment) or further away to the 1000 ms target (i.e., incorrect adjustment). We then calculated the relative percentage of correct adjustments for each feedback condition. The analysis of the behavioral data was performed in JASP 0.7.0.5.6 (JASP Team 2017). The catch-trial accuracy, the performance indices, and the subjective ratings were separately subjected to a paired *t*-test, comparing the informative and uninformative conditions. In case the assumption of normality was violated, we report the Wilcoxon signed-rank test. The trial-to-trial behavioral adjustment was subjected to a 2x2 repeated-measures ANOVA, which included the within-subject factors Context (informative vs. uninformative) and Valence (positive vs. negative).

2.5. EEG

2.5.1. Acquisition and reduction

The EEG was continuously recorded using a BIOSEMI Active-Two system (BioSemi B. V., Amsterdam, the Netherlands) at a sampling rate of 512 Hz. Sixty-four Ag–AgCl (silver-silver chloride) electrodes were used and online referenced to the common-mode sense (CMS)–driven right leg (DRL) ground. All electrodes were mounted in an elastic cap according to the extended International 10–20 EEG system. Six external auxiliary electrodes were included: Four for monitoring the horizontal and vertical electrooculogram (EOG), while two others for the left and right mastoids. EOG electrodes were attached above and below the left eye and on the outer canthi of the two eyes.

A standard data transformation procedure (Keil et al., 2014) was implemented offline to reduce the EEG data using Brain Vision Analyzer 2.0 (Brain Products, GmbH, Munich, Germany). The procedure included the following steps: (i) 50-Hz notch filter (when necessary); (ii) re-referencing using linked-mastoids; (iii) spherical spline interpolation (order of splines = 4, max. degree of Legendre polynomials = 10, lambda = 1e−5) of bad channels which was limited to 6 electrodes (9.3% of the total channels); (iv) 0.1-Hz high-pass filter; (v) data segmentation to epochs of interest (−500/+1000 ms segmentation around the stimulus onset; (vi) eye-blink artifact correction (Gratton, Coles and Donchin, 1983); (vii) baseline correction (−500 ms to feedback onset); (viii) semi-automatic artifact rejection using ±100 μV criterion; (ix) ERP averaging; and (x) 30-Hz low-pass filter. The resulting number of trials in the ERP averages are as follows: 41.2 (*SD* = 5.98) for positive feedback and 48.3 (*SD* = 5.21) for negative feedback in the informative condition; 43.7 (*SD* = 3.97) for positive feedback and 43.6 (*SD* = 5.04) for negative feedback in the uninformative condition.

2.5.2. ERPs

The quantification of the ERP components was based on the electrophysiological properties of the current data set and was in accordance with our own previous work (Walentowska et al., 2016), as well as with many previous ERP studies (e.g., Aarts and Pourtois, 2012; Bismark et al., 2013; Ferdinand et al., 2012; von Borries et al., 2013; Yeung and Sanfey, 2004). For the feedback-locked ERPs, we quantified the FRN as the mean voltage within 250–300 ms after feedback onset at electrodes Fz and FCz (pooled together) and the P3 as the mean voltage within 300–400 ms after feedback onset over the CPz and Pz electrodes (pooled together). These quantified ERP components were then subjected to a 2x2 repeated-measures ANOVAs using JASP, which included the within-subject factors Context and Valence. Significant interactions were then followed up with a post-hoc paired *t*-test. The main and interaction effects are reported first, followed by the post-hoc tests.

2.5.3. PCA

Individual feedback-locked ERPs were subjected to a recommended two-step sequential PCA (Spencer et al., 1999, 2001) using the ERP PCA Toolkit (EP Toolkit, version 2.80; Dien, 2010b) running in Matlab R2013b (MathWorks Inc., Natick, MA, USA). The procedure began with a temporal Promax rotation to capture the variance across the time points from the average ERP data, followed by a spatial Infomax (ICA) rotation to obtain the variance of the spatial distribution of the data across the 64 recording sites (Dien, 2010a).

A total of 88 temporospatial factor combinations were generated, which included 22 temporal factors x 4 spatial factors based on the Scree plot. These factors were further reduced using an automated windowing step, which screened out the factors whose variance accounted was below the minimum 0.5% threshold. Only the PCA factor combinations surviving this windowing step and resembling the FRN and P3 components were selected for statistical testing. To this end, the factors were reconstructed back into voltage space, in which the voltage accounted for at the peak time point and channel were transparently evaluated as ERP waveforms. Factors whose peak latencies and channels coincided to the canonical time course and scalp distribution of the FRN and P3 components were tested.

The PCA factors were analyzed using the robust statistics function of the EP toolkit. This function implements ANOVAs that are robust against violations of statistical assumptions. It also includes the following features: (i) trimmed means and winsorized covariances that protect against outliers; (ii) a bootstrapping routine that estimates the population distribution instead of assuming the normality of this distribution; and (iii) a Welch–James approximate degrees-of-freedom statistic that does not assume the homogeneity of error variance (Dien, 2010b). The robust 2x2 repeated-measures ANOVA also included the same within-subject factors of Context and Valence. The *p*-value was adjusted with the Bonferroni correction for multiple comparisons. Follow up tests for significant interactions are also reported. In case the interaction effect needed better characterization of its source, a robust *t*-test was performed in R Studio using the Yuen test (Yuen, 1974) of the *WRS2* (Wilcox, 2012) package. We chose this particular test because it allows for mean trimming, making the analysis consistent with the parameters implemented in the robust ANOVA of the EP Toolkit (i.e., applying 0.05 trimming level). Difference scores for each of the factors (i.e., context and valence) were calculated and tested using the Yuen function for a paired samples robust *t*-test.

2.6. Multivariate multiple regression analysis

The multivariate multiple linear regression was performed in R Studio (RStudio Team, 2015) using the *car* package (Fox and Weisberg, 2011). The outcome variables included the transformed ERP components (i.e., ΔFRN and ΔP3), whereas the predictor variables included the transformed ratings for goal informativeness (VAS INF) and affective evaluations (VAS VAL). Data transformations for the outcome and predictor variables were conducted to reduce the number of levels per factor and to directly test our hypothesis. These transformations followed specific steps to take into account the outcome of the main statistical analysis (ANOVA; see Results section). The ΔFRN captures the interaction of valence and context, and was calculated by first calculating the valence difference (negative minus positive) at each context, and subsequently calculating the difference of this difference scores across contexts (informative minus uninformative). The ΔP3 captures the main effect of context and was computed by calculating the difference score for the context factor (informative minus uninformative) irrespective of valence (i.e., negative and positive feedback was collapsed). For the VAS INF, the difference rating for the context factor was calculated. For the VAS VAL, the same data transformation as for the ΔFRN was performed. Pillai-Bartlett trace (also known as Pillai's trace; Pillai, 1955), which is considered to be generally robust and powerful against assumption violations (Pituch and Stevens, 2016), was used as a multivariate test statistic.

3. Results

3.1. Behavioral results

Catch-trial accuracy was high and comparable between the informative (*Mdn* = 100%, *SEM* = 0.781) and uninformative *(Mdn* = 100%, *SEM* = 1.198) conditions, $W = 91.5$, $p = .076$, $r = 0.525$, suggesting that participants attended to the feedback equally well in both conditions, which was an important pre-requisite for further analyses.

Participants were able to correctly estimate the 1-s target time, but did it slightly better in the informative (*M* = 990.8 ms, *SEM* = 5.492) than in the uninformative condition (*M* = 1024.9 ms, *SEM* = 22.317), $t_{(43)} = -.769$, $p = .042$, $d = -.267$. With regard to accuracy (i.e., correct responses expressed in percentages), participants reached the expected 50% level in the uninformative condition (*Mdn* = 50%, *SEM* = 0.138), $W = 134$, $p = .652$, $r = -0.107$. Their performance was slightly, but consistently, worse in the informative condition (*M* = 45.42%, *SEM* = 0.746), $t_{(43)} = 6.142$, $p < .001$, $d = 0.926$, based on the specific calibration procedure used in this condition. This suggests that on average, participants received slightly more negative feedback in the informative than in the uninformative condition. However, a control analysis was run to ascertain that this slim asymmetry could not easily explain the ERP results found for the FRN and P3 components.[3]

Trial-to-trial behavioral adjustment revealed a significant main effect of Valence, $F_{(1,43)} = 437.03$, $p < .001$, $\eta p^2 = 0.910$, but not Context,

[3] We performed a linear mixed-effects analysis to model and assess the effect of reward probability (at the feedback level) on the feedback-locked ERP components. As reported in the Supplementary Materials, reward probability (i.e., percentage of positive relative to negative feedback) did not significantly predict the amplitude variations of the FRN and P3 components found as a function of relevance, suggesting that this variable did not simply mask or conflate the modulatory effect created by relevance (see ERP results). Furthermore, the results of this control analysis were in perfect agreement with those obtained using the repeated-measures ANOVA, and reported in the main text (see Results section).

$F_{(1,43)} = 1.884$, $p = .177$, $\eta p^2 = 0.042$. More importantly, a significant Valence x Context interaction, $F_{(1,43)} = 313.25$, $p < .001$, $\eta p^2 = 0.88$, was observed. Post hoc *t*-test showed, as expected, that significantly more correct adjustments were made following negative (*M* = 57.37%, *SEM* = 0.69) than positive feedback (*M* = 36.79 %, *SEM* = 0.75), $t_{(43)} = 20.905$, $p < .001$, $d = 3.152$. Furthermore, follow-up *t*-tests for the significant interaction revealed that in the informative condition, participants showed more correct adjustments after negative feedback (*M* = 66.05%, *SEM* = 0.843) than after positive feedback (*M* = 27.2%, *SEM* = 0.977), $t_{(43)} = 28.58$, $p < .001$, $d = 4.308$. No such difference was found, however, in the uninformative condition $t_{(43)} = 1.54$, $p = .131$, $d = 0.232$, as there were no clear better (or worse) adjustments after negative (*M* = 48.69%, *SEM* = .885) than after positive feedback (*M* = 46.39%, *SEM* = 1.057).

3.2. Feedback goal informativeness and affective evaluations

Post-block ratings of feedback's informativeness revealed that the feedback provided in the informative condition (*M* = 73.14, *SEM* = 3.34) was evaluated as more reflective of actual performance than in the uninformative condition (*M* = 36.42, *SEM* = 3.06), $t_{(43)} = 8.739$, $p < .001$, $d = 1.263$. The result was corroborated by the post-experiment ratings (see Fig. 2A), which showed that feedback provided in the informative condition (*Mdn* = 79.5, *SEM* = 3.28) was also evaluated as more representative of actual performance than in the uninformative condition (*Mdn* = 33.5, *SEM* = 4.01), *W* = 906.0, $p < .001$, $r = 0.830$. Additionally, the positive feedback (see Fig. 2B) was liked significantly less by the participants in the uninformative (*Mdn* = 63.5, *SEM* = 3.63) than in the informative condition (*Mdn* = 86.5, *SEM* = 2.34), *W* = 929.5, $p < .001$, $r = 0.878$. Conversely, the negative feedback (see Fig. 2C) was liked significantly more in the uninformative (*Mdn* = 31.0, *SEM* = 2.74) than in the informative condition (*Mdn* = 16.0, *SEM* = 2.37), *W* = 177.0, $p < .001$, $r = -0.642$, suggesting a lower valence-based affective polarization for uninformative than informative feedback.

3.3. ERP results[4]

3.3.1. FRN

The ANOVA showed significant main effects of Context, $F_{(1,43)} = 30.26$, $p < .001$, $\eta_p^2 = 0.413$, and Valence, $F_{(1,43)} = 67.83$, $p < .001$, $\eta_p^2 = 0.612$ (see Fig. 3). More importantly, a significant Context x Valence interaction, $F_{(1,43)} = 19.82$, $p < .001$, $\eta_p^2 = 0.316$, was found. Post hoc *t*-tests revealed that the FRN's amplitude was overall significantly less negative in the informative (*M* = 6.31 μV, *SEM* = 0.62) than in the uninformative condition (*M* = 3.69 μV, *SEM* = 0.55), $t_{(43)} = 5.500$, $p < .001$, $d = 0.829$. Additionally, as expected, it was significantly more negative for the negative (*M* = 3.48 μV, *SEM* = 0.52) than the positive feedback (*M* = 6.52 μV, *SEM* = 0.61), $t_{(43)} = -8.236$, $p < .001$, $d = -1.242$. Follow-up *t*-tests for the significant interaction revealed that the negative feedback elicited a significantly less negative FRN amplitude in the informative (*M* = 4.08 μV, *SEM* = 0.66) than in the uninformative condition (*M* = 2.87 μV, *SEM* = 0.49), $t_{(43)} = 2.307$, $p = .026$, $d = 0.348$. Similarly, the positive feedback elicited a significantly less negative amplitude in the informative (*M* = 8.54 μV, *SEM* = 0.68) than in the uninformative condition (*M* = 4.50 μV, *SEM* = 0.68), $t_{(43)} = 6.540$, $p < .001$, $d = 0.986$. Moreover, more negative amplitude values were recorded for the negative than the positive feedback both in the informative, $t_{(43)} = -8.651$, $p < .001$, $d = -1.304$, and the uninformative conditions, $t_{(43)} = -3.571$, $p < .001$, $d = -.538$. Additionally, when computing the FRN as a difference between negative and positive feedback, the component was significantly less negative in the uninformative (*M* = −1.63 μV, *SEM* = 0.46) than in the informative condition (*M* = −4.46 μV, *SEM* = 0.52), $t_{(43)} = -4.452$, $p < .001$, $d = -.671$.

[4] Since we also previously found that goal relevance could also influence internal PM at the error-related negativity (ERN) level (Walentowska et al., 2016), we performed an auxiliary analysis on the response-locked ERP data and compared them between the two main relevance conditions (see Supplementary Materials). However, this analysis failed to reveal a significant effect of goal relevance on the ERN and CRN (correct-related negativity).

3.3.2. P3

The ANOVA showed significant main effects of Context, $F_{(1,43)} = 51.21$, $p < .001$, $\eta_p^2 = 0.544$, and Valence, $F_{(1,43)} = 34.79$, $p < .001$, $\eta_p^2 = 0.447$ (see Fig. 4). However, the Context x Valence interaction was not significant, $F_{(1,43)} = 0.21$, $p = .646$, $\eta_p^2 = 0.005$. Post hoc *t*-tests revealed that the P3's amplitude was overall significantly lower in the uninformative (*M* = 6.13 μV, *SEM* = 0.64) than in the informative condition (*M* = 11.22 μV, *SEM* = 0.72), $t_{(43)} = 7.156$, $p < .001$, $d = 1.079$. Moreover, it was significantly larger for the positive (*M* = 9.79 μV, *SEM* = 0.64) than the negative feedback (*M* = 7.56 μV, *SEM* = 0.58), $t_{(43)} = 5.898$, $p < .001$, $d = 0.889$.

3.3.3. Temporospatial PCA factors

Six temporospatial factor were recognized to closely correspond to the FRN and P3 components in terms of time course and scalp distribution (see Table 1 and Fig. 5). One of them could unequivocally be attributed to the FRN, whereas five of them captured complex spatiotemporal variations of the P3.

3.3.3.1. PCA factor corresponding to FRN. PCA factor TF07SF1 closely corresponded to the FRN component as its amplitude peaked at 240 ms over the fronto-central area, maximal at FCz (see Fig. 5A). The robust ANOVA revealed a significant main effect of Context (uncorrected), $T_{WJt}/c(1.0,39.0) = 5.49$, $p = .024$, showing less factor negativity in the uninformative (*M* = 2.49 μV) than in the informative condition (*M* = 1.58 μV). The main effect of Valence was also significant (corrected), $T_{WJt}/c(1.0,39.0) = 39.06$, $p < .001$, showing more factor negativity for the negative (*M* = 0.95 μV) than the positive feedback (*M* = 3.12 μV). More importantly, the Context x Valence interaction was significant (corrected), $T_{WJt}/c(1.0,39.0) = 11.75$, $p = .0004$. Follow-up tests for this interaction revealed that for the negative feedback, the factor showed significantly less negativity (corrected) in the uninformative (*M* = 1.82 μV) than in the informative (*M* = 0.09 μV) condition, $T_{WJt}/c(1.0,39.0) = 12.15$, $p = .0014$. The positive feedback, on the other hand, did not elicit significant factor negativity between the uninformative (*M* = 3.17 μV) and the informative (*M* = 3.08 μV) conditions, $T_{WJt}/c(1.0,39.0) = 0.04$, $p = .84$. Furthermore, in the uninformative condition, the factor showed significantly more negativity (corrected) for the negative (*M* = 1.82 μV) than the positive feedback (*M* = 3.17 μV), $T_{WJt}/c(1.0,39.0) = 11.28$, $p = .0006$. Likewise, in the informative condition, it showed significantly more negativity (corrected) for the negative (*M* = 0.09 μV) than the positive feedback (*M* = 3.08 μV), $T_{WJt}/c(1.0,39.0) = 11.28$, $p < .001$.

3.3.3.2. PCA factors corresponding to P3. PCA factor TF02SF1 closely corresponded to the P3 component as its amplitude peaked at 340 ms over the central area, maximal at Cz (see Fig. 5B). The robust ANOVA revealed a significant main effect of Context (corrected), $T_{WJt}/c(1.0,39.0) = 72.57$, $p < .001$, showing less factor positivity in the uninformative (*M* = 6.14 μV) than in the informative condition (*M* = 11.71 μV). Similarly, the main effect of Valence was significant (corrected), $T_{WJt}/c(1.0,39.0) = 38.30$, $p < .001$, showing more factor positivity for the positive (*M* = 10.22 μV) than the negative feedback (*M* = 7.62 μV). The Context x Valence interaction was also significant (uncorrected), $T_{WJt}/c(1.0,39.0) = 5.49$, $p = .026$. Follow-up tests for this interaction revealed that for negative feedback, the factor showed significantly less positivity (corrected) in the uninformative (*M* = 5.18 μV) than in the informative condition (*M* = 10.07 μV), $T_{WJt}/c(1.0,39.0) = 50.82$, $p < .001$. Likewise, for the positive feedback, the factor showed significantly less positivity (corrected) in the uninformative (*M* = 7.10 μV) than in the

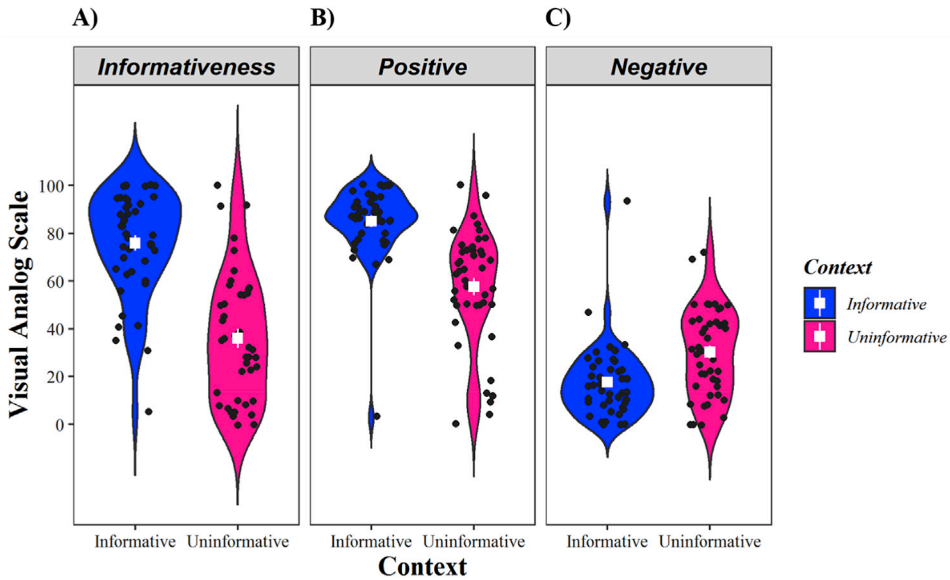

Fig. 2. Subjective ratings (post-task). (A) Results showed that the feedback provided in the informative condition was evaluated as more reflective of actual performance than in the uninformative condition. (B) If positive, it was also liked more in the informative condition. (C) If negative, it was disliked more in the informative condition. All ratings were assessed using a visual analog scale, ranging from 0 to 100.

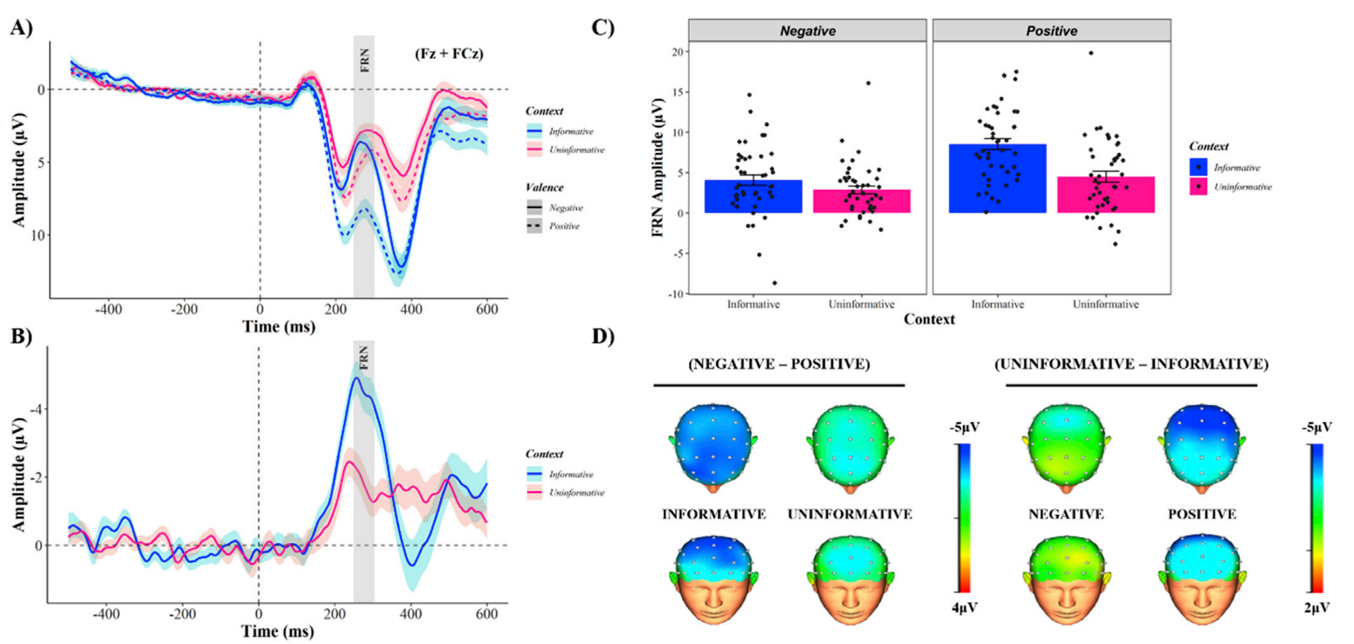

Fig. 3. FRN results. (A) Grand average ERP waveforms (±1 SEM) for channels Fz & FCz (pooled together) shown separately for each context and valence. (B) A difference wave (negative-positive feedback) is shown separately for informative and uninformative context. Note that negativity is plotted upwards. For visualization purposes only, a 20-Hz low-pass filter was applied to the waveforms. (C) Mean FRN amplitude (±1 SEM) for each of the four main conditions. The FRN was computed as a mean ERP activity in the 250–300 ms time window following feedback onset (Fz & FCz). (D) The corresponding frontal and horizontal topographical scalp maps of the FRN are shown.

informative condition ($M = 13.34$ μV), $T_{WJt}/c(1.0,39.0) = 70.92$, $p < .001$. Furthermore, in the uninformative condition, the factor showed significantly more positivity (corrected) for the positive ($M = 7.10$ μV) than the negative feedback ($M = 5.18$ μV), $T_{WJt}/c(1.0,39.0) = 21.76$, $p < .001$. Similarly, in the informative condition, it showed significantly more positivity (corrected) for the positive ($M = 13.34$ μV) than the negative feedback ($M = 10.07$ μV), $T_{WJt}/c(1.0,39.0) = 30.69$, $p < .001$. Moreover, when computing the difference between positive and negative feedback, a robust post hoc *t*-test revealed that the PCA factor showed significantly less positivity in the uninformative ($M = 1.90$, $SEM = 0.39$) than in the informative condition ($M = 3.01$, $SEM = 0.57$), $t_{(39)} = 2.108$, $p = .042$, $d = 0.24$. When computing the difference between informative and uninformative feedback, a robust post hoc *t*-test revealed that the PCA factor showed significantly more positivity for the positive ($M = 6.02$, $SEM = 0.74$) than for the negative feedback ($M = 4.76$, $SEM = 0.72$), $t_{(39)} = 2.244$, $p = .03$, $d = 0.19$.

PCA factor TF02SF2 closely corresponded to the P3 component as its amplitude peaked at 340 ms over the parietal area, maximal at POz (see Fig. 5C). The robust ANOVA showed, however, neither a significant main effect of Context, $T_{WJt}/c(1.0,39.0) = 1.05$, $p = .32$, nor of Valence, $T_{WJt}/$

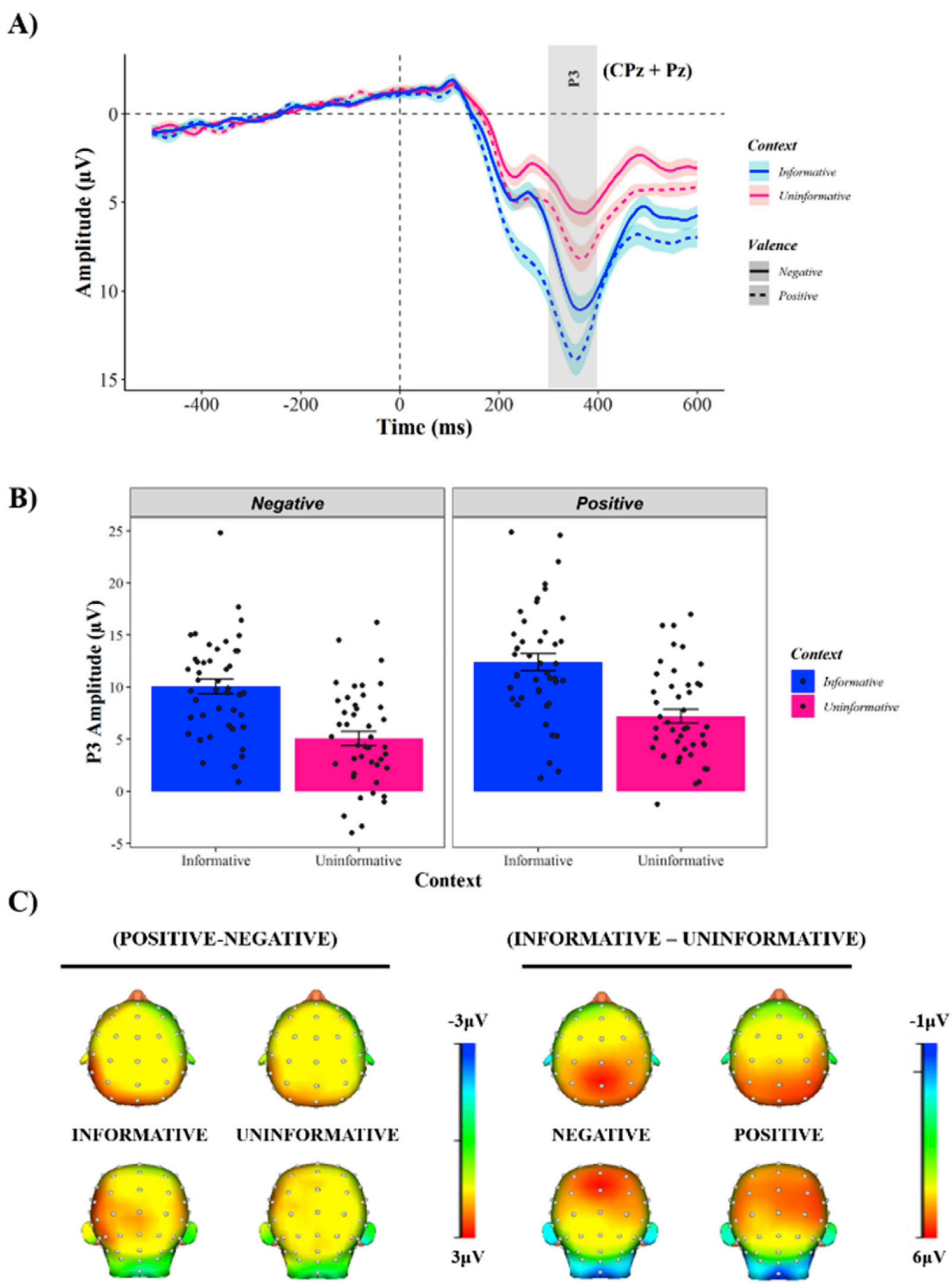

Fig. 4. P3 results. (A) Grand average ERP waveforms (±1 SEM) for channels CPz & Pz (pooled together) shown separately for each context and valence. Note that negativity is plotted upwards. For visualization purposes only, a 20-Hz low-pass filter was applied to the waveforms. (B) Mean amplitude of the P3 (±1 SEM) for each of the four main conditions. The P3 was computed as a mean ERP activity in the 300–400 ms time window following feedback onset (CPz & Pz). (C) The corresponding frontal and horizontal topographical scalp maps of the P3 component are shown.

Table 1
Temporospatial PCA factors. The table presents the six temporospatial factors selected after PCA for data analysis. Note that "SF" stands for spatial factor and "TF" for temporal factor.

PCA Factor	Associated ERP component	Peak Latency (ms)	Peak Channel	Variance explained (%)
TF07SF1	FRN	240	FCz	2.3%
TF02SF1	P3	340	Cz	18.7%
TF02SF2	P3	340	POz	2.0%
TF03SF2	P3	477	POz	1.8%
TF06SF1	P3	402	Fz	2.6%
TF12SF1	P3	363	Fz	0.93%

c(1.0,39.0) = 1.99, p = .16. Furthermore, no significant Context x Valence interaction was found, $T_{WJt}/c(1.0,39.0) = 0.26$, $p = .62$.

PCA factor TF03SF2 closely corresponded to the P3 component as its amplitude peaked at 477 ms over the parietal area, maximal at POz (see Fig. 5D). The robust ANOVA revealed a significant main effect of Context (uncorrected), $T_{WJt}/c(1.0,39.0) = 5.14$, $p = .027$, showing slightly lower factor positivity in the uninformative ($M = 1.41$ µV) than in the informative condition ($M = 1.89$ µV). The main effect of Valence only reached one-tailed significance (uncorrected), $T_{WJt}/c(1.0,39.0) = 3.82$, $p = .03$, showing a slightly lower factor positivity for the positive ($M = 1.49$ µV) than the negative feedback ($M = 1.81$ µV). The Context x Valence interaction was also significant (uncorrected), $T_{WJt}/c(1.0,39.0) = 5.49$, $p = .026$. Follow-up tests for this interaction revealed that for negative feedback, the factor showed significantly less positivity (corrected) in the

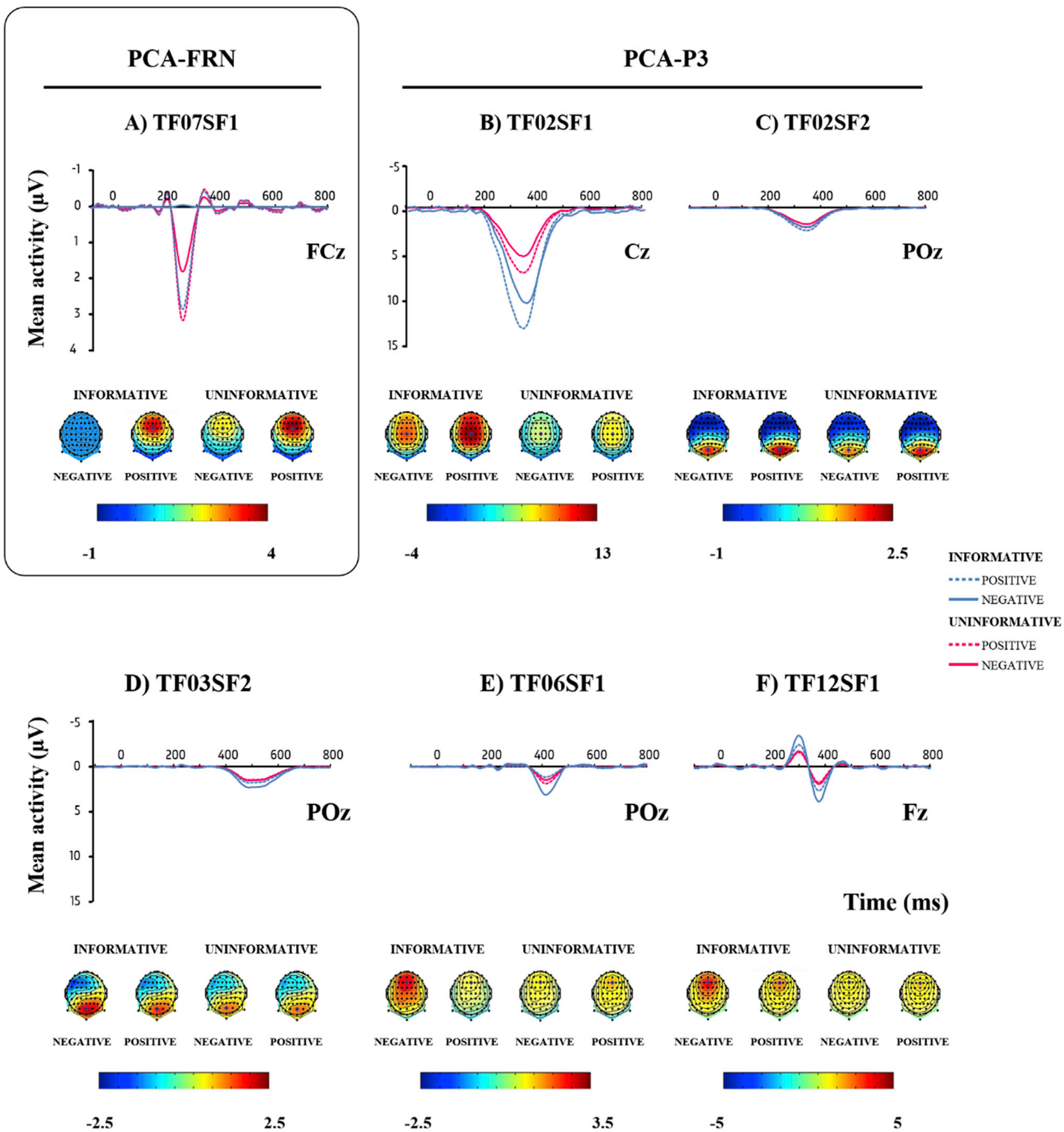

Fig. 5. Results of the PCA. (A) For the FRN, a main and unique temporospatial factor was identified. (B–F) In comparison, for the P3, several temporospatial components were revealed. Note that negativity is plotted upwards. For each factor, the corresponding horizontal topographical map is shown, separately for each level of goal informativeness and valence.

uninformative ($M = 1.42$ μV) than in the informative condition ($M = 2.20$ μV), $T_{WJt}/c(1.0,39.0) = 9.27$, $p = .0062$. In comparison, for the positive feedback, no significant differences in the factor amplitude between the informative ($M = 1.59$ μV) and the uninformative ($M = 1.39$ μV) conditions, $T_{WJt}/c(1.0,39.0) = 0.63$, $p = .42$. Furthermore, in the uninformative condition, the factor showed no significant differences in amplitude for the positive ($M = 1.42$ μV) than the negative feedback ($M = 1.39$ μV), $T_{WJt}/c(1.0,39.0) = 0.02$, $p = .89$. In the informative condition, on the other hand, it showed significantly more positivity (uncorrected) for the negative ($M = 2.20$ μV) than the positive feedback ($M = 1.59$ μV), $T_{WJt}/c(1.0,39.0) = 7.47$, $p = .017$.

PCA factor TF06SF1 closely corresponded to the P3 component as its amplitude peaked at 402 ms over the frontal area, maximal at Fz (see Fig. 5E). The robust ANOVA revealed a significant main effect of Context, albeit one-way (uncorrected), $T_{WJt}/c(1.0,39.0) = 3.46$, $p = .04$, showing slightly lower factor positivity in the uninformative ($M = 1.53$ μV) than in the informative condition ($M = 2.04$ μV). The main effect of Valence was not significant, $T_{WJt}/c(1.0,39.0) = 2.46$, $p = .12$. The Context x Valence interaction was also significant (corrected), $T_{WJt}/c(1.0,39.0) = 13.51$, $p = .0008$. Follow-up tests for this interaction revealed that for negative feedback, the factor showed significantly less positivity (corrected) in the uninformative ($M = 1.22$ μV) than in the informative condition ($M = 2.98$ μV), $T_{WJt}/c(1.0,39.0) = 14.64$, $p = 0.0004$. For the positive feedback, on the other hand, it showed significantly less positivity, albeit one-way (uncorrected) in the informative ($M = 1.10$ μV) than in the uninformative condition ($M = 1.84$ μV), $T_{WJt}/c(1.0,39.0) = 3.24$, $p = .04$. Furthermore, in the uninformative condition, the factor showed no significant differences in amplitude for the negative ($M = 1.22$ μV) and the positive feedback ($M = 1.84$ μV), $T_{WJt}/c(1.0,39.0) = 1.74$, $p = .20$. In contrast, in the informative condition, it showed significantly more positivity (corrected) for the negative ($M = 2.98$ μV) than the positive feedback ($M = 1.10$ μV), $T_{WJt}/c(1.0,39.0) = 10.77$, $p = .0024$.

PCA factor TF12SF1 closely corresponded to the P3 component as its amplitude peaks at 363 ms over the frontal area, maximal at Fz (see Fig. 5F). The robust ANOVA revealed a significant main effect of Context (corrected), $T_{WJt}/c(1.0,39.0) = 15.24$, $p = .0002$, showing less factor positivity in the uninformative ($M = 1.95$ μV) than in the informative condition ($M = 3.14$ μV). The main effect of Valence only reached one-tailed significance (uncorrected), $T_{WJt}/c(1.0,39.0) = 3.49$, $p = .035$, showing a slightly lower factor positivity for the positive ($M = 2.29$ μV) than the negative feedback ($M = 2.79$ μV). The Context x Valence interaction was also significant (uncorrected), $T_{WJt}/c(1.0,39.0) = 7.55$, $p = .0088$. Follow-up tests for this interaction revealed that for negative feedback, the factor showed significantly less positivity (corrected) in the uninformative ($M = 1.86$ μV) than in the informative condition ($M = 3.73$ μV), $T_{WJt}/c(1.0,39.0) = 15.92$, $p = .0002$. For the positive feedback, it also showed slightly less positivity, albeit one-way significant (uncorrected) in the uninformative ($M = 2.03$ μV) than in the informative condition ($M = 2.56$ μV), $T_{WJt}/c(1.0,39.0) = 3.15$, $p = .0405$. Moreover, in the uninformative condition, the factor showed no significant differences in amplitude for the negative ($M = 1.86$ μV) and the positive feedback ($M = 2.03$ μV), $T_{WJt}/c(1.0,39.0) = 0.35$, $p = .57$. Inversely, in the informative condition, it showed significantly more positivity (uncorrected), for the negative feedback ($M = 3.73$ μV) than the positive feedback ($M = 2.56$ μV), $T_{WJt}/c(1.0,39.0) = 7.57$, $p = .0090$.

3.4. Zero-order correlations

The outcome variables (i.e., ΔFRN and ΔP3) and predictor variables (i.e., VAS INF & VAS VAL) showed a significant low to high degree of correlations among each other (see Table 2).

3.5. Multivariate multiple regression results

A significant relationship was found between the two ERP effects (i.e., ΔFRN and ΔP3) and the VAS INF, $F_{(2,40)} = 3.655$, $p = .0349$, but not with the VAS VAL, $F_{(2,40)} = 0.020$, $p = .4182$. A univariate multiple regression analysis revealed that the ΔFRN was significantly predicted, $F_{(2,41)} = 3.293$, $p = .0472$, with an $R^2 = 0.1384$, by VAS INF ($p = .04$) but not VAS VAL ($p = .90$; see Fig. 6A). Likewise, the ΔP3 was significantly predicted, $F_{(2,41)} = 6.349$, $p = .004$, with an $R^2 = 0.2365$, by VAS INF ($p = .03$) but not VAS VAL ($p = .39$; see Fig. 6B). Table 3 reports the estimates (standard errors) and the p-values for each of the predictors, separately for the FRN and P3 components.

4. Discussion

In this study, we sought to assess whether the effect of goal relevance in the sense of goal informativeness on the FRN and P3 components was (i) identical for these two successive feedback-locked ERP components and (ii) related to valence processing. To this aim, we administered to a large group of participants a modified version of the time estimation task (Miltner et al., 1997). Using a within-subject design, the goal informativeness of the performance feedback in this task varied across blocks (whereas the task and stimuli remained the same). Particularly, feedback following time estimation was informative of participants' actual task performance in some blocks (and thus enabled them to assess the satisfaction's status of their goal), but not in others. The behavioral results confirmed the successful manipulation of goal relevance in the sense of informativeness: At the subjective level, participants rated the feedback in the uninformative condition as being less reflective of their actual performance than in the informative condition. Moreover, the affective polarization of the feedback depending on its valence was lowered in the uninformative compared to the informative condition. These results were obtained despite the fact that the feedback in both conditions was equally goal relevant in the sense of task relevance (in that participants had to process it in order to implement the secondary task) and that participants clearly paid attention to its value (see catch trials accuracy). Hence, the amount of goal informativeness clearly differed between the two conditions whereas task relevance and attention to feedback were equal (see also Walentowska et al., 2016). Additionally, the participants generally adjusted their estimates following the receipt of the feedback. This post-feedback behavioral adjustment was evident in their execution of more correct adjustments following negative than positive feedback. Crucially, this adjustment was only present when the feedback was informative of the satisfaction status of their goal. Once this feedback ceased to be informative, participants no longer adjusted their behavior depending on its valence.

Our new ERP results confirmed that goal informativeness substantially influenced the amplitude of the FRN and P3 components. More specifically, we found a less pronounced valence-driven FRN effect when feedback was goal uninformative than when it was informative. Moreover, decreasing goal informativeness led to a lower P3 component, for positive and negative outcomes alike, suggesting a dissociation between these two successive ERP components during PM (see also Severo et al., 2018, for a similar conclusion). This dissociation was also corroborated by a complementary PCA, which could disentangle the reduction in valence processing at the FRN level from a more global (i.e., valence-unspecific) decrease of feedback processing at the P3 level when the feedback was uninformative. Moreover, a multivariate regression analysis revealed that goal informativeness, unlike valence, was the only significant predictor of the difference in amplitude changes of both the FRN and P3 components between the two main conditions. Here after, we provide a more in-depth discussion of these new ERP results and their possible implications for current neurophysiological models of PM.

An interesting result of the present study is the decreased affective polarization of the feedback at the subjective level when it was uninformative of the satisfaction status of the goal (i.e., to correctly estimate the time). This result is compatible with appraisal theories of emotions, which hold that emotional stimuli, including performance feedback, are rapidly evaluated in terms of relevance for the individual's needs, goals, and values (Kreibig et al., 2012; Moors et al., 2013). In this framework, positive affect is typically elicited by the goal-conducive outcomes or situations (such as positive feedback), whereas negative affect is typically elicited by goal-obstructive ones (such as negative feedback). Moreover, these opposing affects are not fixed or rigid, but critically depend on whether the stimulus informs about the satisfaction status of pursued goals (see also Kreibig et al., 2012; Scherer, 2001). Accordingly, a decreased affective evaluation of the feedback can be observed when it remains uninformative of goal attainment. This effect was evident in the present case when the feedback in the uninformative condition did not allow participants to assess whether their time estimation was correct or not.

At the ERP level, we recorded a conspicuous FRN component, whose amplitude varied with feedback's valence in the informative condition

Table 2
Correlation matrix. The table summarizes the zero-order correlation among the variables used in the multivariate regression. *p < .05, **p < .01, ***p < .001.

Variables	1	2	3	4
ΔFRN	–			
ΔP3	−0.367*	–		
VAS INF	−0.372*	0.472**	–	
VAS VAL	−0.214	0.382*	0.612***	–

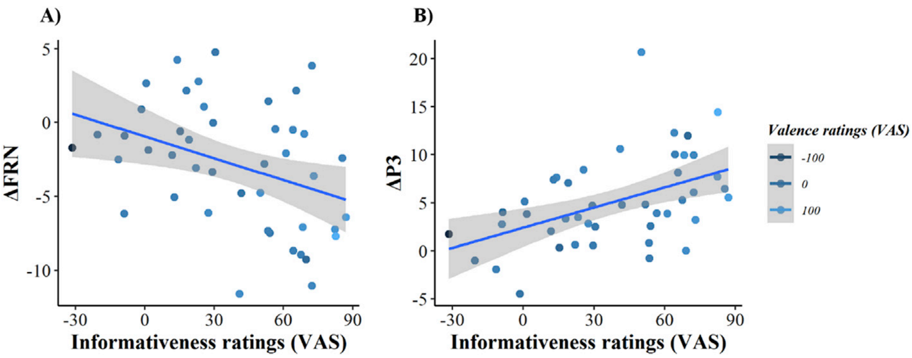

Fig. 6. Results of the univariate multiple regression analysis. (A) The amplitude of the FRN (here computed as the difference between negative and positive feedback, before the goal uninformative feedback was subtracted from the goal informative feedback; see Fig. 3C) was predicted by goal informativeness exclusively, but not valence (see Results). (B) Likewise, the P3 amplitude (here computed as the difference between goal informative and goal uninformative feedback; see Fig. 4B) was only predicted by goal informativeness, but not valence (see Results).

Table 3
Regression estimates. The table summarizes the estimates (standard errors) and the p-values for each of the predictor included in the multivariate multiple regression, separately for the FRN and P3 components.

ERP	Predictor	B	p
	Intercept	−0.95 (0.95)	0.32
ΔFRN	VAS INF (informativeness ratings)	−0.05 (0.02)	0.04*
	VAS VAL (valence ratings)	0.00 (0.02)	0.90
	Intercept	2.36 (1.00)	0.02*
ΔP3	VAS INF (informativeness ratings)	0.06 (0.03)	0.03*
	VAS VAL (valence ratings)	0.01 (0.02)	0.39

only. Compared to positive feedback, negative feedback led to a clear-cut negative component reaching its maximum amplitude 250–300 ms after stimulus onset. This result is in line with many earlier ERP studies that already used the time estimation task (e.g., Boksem et al., 2011; Boksem et al., 2012; Miltner et al., 1997; Pfabigan and Han, 2019; Pfabigan et al., 2015, 2018, 2014), as well as with others using different tasks (Luque et al., 2012; Luu et al., 2004). Moreover, when we used a difference wave (i.e., amplitude difference between the negative and positive feedback), a large residual negative activity was found when the feedback was informative. The topography of this negativity was entirely compatible with the FRN, being characterized by a fronto-central scalp distribution (see Gheza et al., 2018; Holroyd and Krigolson, 2007; San Martín, 2012). Strikingly, when the feedback was uninformative, this effect was largely suppressed, even though the feedback was still task relevant, thereby suggesting that the automatic evaluation of the action outcome as good or bad could be suppressed in case participants knew (beforehand) that this feedback was not informative about their previous actions. As such, this result accords well with our previous findings based on a speeded Go/No Go Task (Walentowska et al., 2016) and extends them to another experimental contexts in which the inhibition of a pre-potent response is not required. Importantly, this finding therefore suggests that this down-regulation of feedback-based PM at the FRN level is not confined to the use of this specific task testing executive functions.

Alternatively, it could be argued that by blocking goal informativeness at the feedback level in the uninformative condition, we inevitably decreased the learnability of the task in this condition. Previous models and ERP studies have linked amplitudes variations of the FRN with feedback utilization and/or (reinforcement) learning (Di Gregorio, Ernst and Steinhauser, 2019; Ernst and Steinhauser, 2017, 2018; San Martín, 2012; Walsh and Anderson, 2012). In many situations, learnability and goal informativeness covary at the feedback level, and/or goal informativeness is actually required to enable learnability based on the feedback. Although it remains difficult to formally rule out learnability as an alternative explanation in the present case, we have good reasons to believe that this factor alone is unlikely to explain our new results for the FRN (and P3). First, we used a stringent staircase procedure in the informative condition so that learning across trials was mostly blocked. Learnability was also excluded in the uninformative condition because the feedback was not linked to participants' performance. Second, we failed to observe a difference between the informative and uninformative conditions at the response level (i.e., error-related negativity or ERN, see Supplementary Materials). If learnability was higher in the informative than uninformative condition, then the ERN (upon error commission) ought to be larger in the former condition, which we did not observe however. Finally, a close inspection of subjective ratings (as well as results for the P3 component) suggests that participants also assigned a positive or negative value to the feedback in the uninformative condition, even if this effect was strongly attenuated compared to the informative condition. Accordingly, we suggest that in the uninformative condition, the value of the feedback was probably perceived, but was not informative about the satisfaction status of the pursued goal, and could therefore be downplayed by the participants. It is also interesting to note that the ERP waveforms for all the conditions tended to cluster together at the FRN level, except for the positive feedback in the informative condition (see Fig. 3A). This observation indirectly suggests that the putative top-down devaluation of the feedback in the uninformative condition was probably most effective for positive feedback, even though the results of the multivariate regression analysis clearly showed that informativeness, but not valence, was the driving force of this effect.

It could also be argued that the reduced valence-driven effect at the FRN level for the feedback in the uninformative condition relates to the fact that participants had low control over this feedback. A handful of earlier ERP studies have reported that the FRN's amplitude decreases when an individual's sense of control or agency is systematically reduced (e.g., Bismark et al., 2013; Itagaki and Katayama, 2008; Li et al., 2011; Marco-Pallarés et al., 2010; Martin and Potts, 2011; Yeung et al., 2005). Unlike our study, these previous studies manipulated the sense of agency of the participants to varying degrees and used different gambling-like tasks, which arguably already have low controllability. In our study, by contrast, the time estimation task offered a relatively higher sense of agency to the participants, regardless of the informativeness manipulation. The participants remained engaged in the task across all conditions as demonstrated by the behavioral indices. Moreover, the high catch-trial accuracy in the uninformative condition indicated that the participants still perceived the evaluative feedback as relevant to the task completion (i.e., task relevant). The high sense of agency is similarly echoed in our previous study, where engagement to the speeded Go/No Go Task remained intact despite the informativeness manipulation (Walentowska et al., 2016). Overall, an important contribution of the current study is therefore to show and emphasize that goal informativeness per se, rather than controllability or sense of agency, is likely to be the main factor accounting for the amplitude modulation of the FRN. Moreover, our results are the first to show that this modulatory effect of goal informativeness during feedback processing is not circumscribed to the FRN, but can also influence the subsequent P3 component, even though these two successive ERP components capture different PM processes, as shown by the PCA results.

It is also important to point out that some previous studies already manipulated the feedback's informativeness by parametrically varying its content - either presenting a binary information of response's accuracy or a more complex one about the direction of its deviation (see Cockburn and Holroyd, 2018; see also Frömer et al., 2016; Li et al., 2018; Luft et al., 2014). These studies employed different tasks and (error) feedback types, and reported mixed effects of graded feedback information on the FRN. In two studies, the FRN's amplitude increased as a function of increasing the feedback's error information in a time estimation task (Luft et al., 2014) or a virtual throwing task (Frömer et al., 2016). In contrast, Cockburn and Holroyd (2018) reported a decrease in the FRN's amplitude when the feedback conveyed more information about the deviation during time estimation. Another study (Li et al., 2018) also reported a smaller FRN-like ERP component for cues indicating 100% feedback reliability than those indicating 70% or 50%. Accordingly, it seems that the feedback's informativeness does not unconditionally increase the FRN. Unlike in these previous studies, we only contrasted informative with uninformative feedback and did not introduce graded feedback in our study. Even though it remains speculative at this stage to account for this discrepancy across existing studies, it appears plausible to conclude that when a simple (visual) evaluative feedback stimulus is used (Liu et al., 2014; Pfabigan et al., 2019, 2015), and a binary division is made between informative and uninformative feedback, the FRN tends to be larger for the informative feedback (see also Frömer et al., 2016; Luft et al., 2014). Presumably, if complex feedbacks are used and a gradation regarding error information is conveyed by them (Cockburn and Holroyd, 2018), additional monitoring processes could operate in this condition, which could overshadow a simple evaluative coding of the feedback as good or bad at the FRN level. In this context, it appears important to assess whether the subsequent P3 component might also vary depending on the feedback's informativeness besides the FRN, which we found was the case here (but see Cockburn and Holroyd, 2018). Future ERP studies should clarify whether depending on the specific type of feedback information provided to the participants, different monitoring effects vis-à-vis goal informativeness could be evidenced at the FRN (and P3) level.

In line with the FRN effect, goal informativeness also substantially influenced the P3 component, with smaller amplitudes for uninformative than informative feedback. This finding is a replication of our previous results (Walentowska et al., 2016), as well as in line with a recent series of studies (Severo et al., 2017, 2018), where we focused on goal relevance in the sense of goal impact instead of goal informativeness (i.e., second and third components of our theoretical model, as briefly described in the introduction section and in Walentowska et al., 2016). This result dovetails with the assumption that a lower motivational significance was likely attached to performance feedback in the uninformative compared to the informative condition (Nieuwenhuis et al., 2005; San Martín, 2012). However, whether this reduction in feedback processing resulted from decreased attention allocation (to a less salient event) per se or a weaker updating of (feedback) information in the uninformative condition (Donchin and Coles, 1998; Polich, 2007) awaits additional ERP studies.

It should be pointed out, however, that in our previous study (Walentowska et al., 2016), the P3 amplitude was unexpectedly larger for negative than for positive feedback, while in the current and other studies, this was reversed (Severo et al., 2017, 2018). A larger P3 for positive feedback is consistent with several other earlier ERP studies (e.g., Bellebaum and Daum, 2008; Bellebaum et al., 2010; Gu et al., 2011), including some studies that also employed the time estimation task (Pfabigan et al., 2015, 2018). It is worth noting that this valence effect at the P3 level was found as long as the feedback stimuli remained simple and did not carry complex social information (Pfabigan et al., 2019; Pfabigan and Han, 2019). Hence, the discrepancy for the P3 between the present results and our previous findings (Walentowska et al., 2016) could tentatively be attributed to the differences in the feedback stimuli used in these two studies and/or to different task demands. In Walentowska et al. (2016), emotional faces were used as performance feedback during a Go/No Go Task, whereas here, we used simple symbolic stimuli and a time estimation task.

Moreover, although the FRN and P3 components closely followed each other and could therefore capture similar and overlapping PM effects, we used a stringent PCA enabling to establish two dissociable effects for them depending on goal informativeness. More specifically, the PCA allowed us to isolate a unique temporospatial component that nicely captured the early reduction of valence processing at prefrontal leads along the midline following feedback onset when feedback was uninformative (i.e., FRN). Hence, this data-driven analysis confirmed that valence processing was selectively suppressed at the FRN level whenever the performance feedback was uninformative, and this effect was not conflated by the P3. Interestingly, for the FRN component, the PCA also revealed a different result from the standard ERP, which highlights the utility of combining the former analysis with the latter one. More specifically, the PCA (see Fig. 5A) showed that the negative feedback in the informative condition evoked the most deviant negative-going amplitude, in agreement with a FRN effect (Holroyd and Coles, 2002). In contrast, as pointed out earlier, the standard ERP analysis showed that the positive feedback in the informative condition evoked the most deviant positive-going amplitude shift, probably reflecting a RewP effect instead (Proudfit, 2015). These results therefore suggest that the PCA can isolate a specific (sub)component during the FRN-RewP time interval, which is not directly visible when using a standard ERP approach. The PCA identified five different temporospatial components[5] during the P3, with some of them showing a rather similar effect at prefrontal sites compared to the FRN, while other mostly revealed a global reduction of feedback processing at posterior parietal leads when the feedback was uninformative. Accordingly, these results suggest that unlike the FRN, the feedback-locked P3 is likely subtended by multiple components or generators. Some of these components overlap with the FRN (and influence valence processing), whereas others are more easily dissociated from it because of a non-overlapping scalp distribution and electrophysiological time-course. Whether this latter P3 effect reflects attention, regulation, or updating with goal informativeness awaits additional studies. More generally, these results emphasize both the challenge, as well as the added value, of using a PCA to disentangle the FRN from the P3 during PM (Bernat et al., 2008; Foti et al., 2011).

At the theoretical level, our new results are also important because they allow us to confirm the goal relevance framework that was proposed recently by Walentowska et al. (2016), according to which PM is shaped by contextual factors and motivational demands, besides valence and expectedness. In this framework, the FRN component does not simply reflect an unconditional processing of the outcome as being good or bad (e.g., Hajcak et al., 2007). Instead, its amplitude depend on whether the evaluative feedback informs about the satisfaction status of the pursed goal or not. This conclusion is corroborated by the outcome of the multivariate regression analysis, which showed that goal informativeness at the subjective level significantly predicted the amplitude changes of both the FRN and P3 between the informative and uninformative feedback conditions. Remarkably, no such effect was found when valence was used as (concurrent) predictor, thereby lending support to the notion that goal relevance is a superordinate PM component that can influence both valence (FRN) as well as motivational significance (P3) effects of feedback processing.

A few limitations warrant comments. First, as we have mentioned above, the question whether feedback learnability played a role in the differential valence-driven FRN effect between the two main conditions

[5] Intriguingly, one PCA factor stands out as being bi-phasic in comparison to the rest (see Fig. 5), which could raise a question whether this factor actually corresponds to the P3 component. This might be related to the mid-frontal theta oscillations, which are more closely linked to the FRN. The selection of this factor, however, was primarily based on its peak latency (at 363 ms) and channel (at Fz), which still falls within the broad scalp distribution of the component, from fronto-central to parietal sites (Polich, 2007; Ullsperger et al., 2014).

requires further investigation. Future ERP studies could address this by devising experimental designs that could orthogonalize the effects of feedback learnability and goal informativeness. Second, the actual mechanism through which the rapid evaluation of the feedback as good or bad can be downplayed in the uninformative condition remains somewhat elusive and is yet to be closely examined. Although our results suggest that this devaluation can be dissociated from task relevance and attention, additional studies are needed to better understand how this is actually achieved, and, for example, whether metacognitive processes also play a role in it (Wokke et al., 2017).

To sum up, the present study demonstrated by means of a time estimation task that goal relevance in the sense of goal informativeness is an important determinant of PM. Lowering this factor in the uninformative condition led to a suppression of the valence-driven effect normally found at the FRN level (in the informative condition), hence indicating that it occurred rapidly following feedback onset. Further, the subsequent P3 component was smaller for uninformative than informative feedback, yet regardless of the specific value carried by it. Even though these two neurophysiological effects were dissociable from each other, our results also suggest that they were both influenced by a common, valence-unspecific and superordinate PM process related to goal informativeness. Moreover, these ERP results were found despite the fact that stimuli and task demands were kept similar between the two main conditions, and participants also attended to the feedback stimulus in the uninformative condition. We suggest that during time estimation, participants could temporarily devalue the performance feedback when it was provided in the uninformative context. This devaluation was probably functional as it allowed them to lower the value (FRN) and motivational significance (P3) of the feedback because the satisfaction's status of their goal could not be extracted from it. More generally, these results add to a growing literature in psychophysiology and cognitive neuroscience that seeks to better incorporate and model effects of context and motivation on PM, besides those related to valence and expectedness only.

Data Availability Statement

The data and the codes that support the findings of this study are openly available in Open Science Framework (OSF) at https://osf.io/c9fzy/ (doi: 10.17605/OSF.IO/C9FZY).

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Mario Carlo Severo: Conceptualization, Methodology, Software, Investigation, Formal analysis, Data curation, Writing - original draft, Visualization. **Katharina Paul:** Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - review & editing. **Wioleta Walentowska:** Conceptualization, Methodology, Writing - review & editing. **Agnes Moors:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Gilles Pourtois:** Conceptualization, Methodology, Data curation, Writing - original draft, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.116857.

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